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Experiments in regard to the supposed "suction pump" + + + + +

EXPERIMENTS IN REGARD TO THE SUPPOSED "SUCTION PUMP" ACTION OF THE MAMMALIAN HEART. By H. NEWELL MARTIN, D. Sc., M. D., M. A., F. R. S., Professor in the Johns Hopkins University, and FRANK DONALDSON, Jr., B. A., M. D., formerly Graduate Scholar of the same. With Plate V.

That the heart acts not only as a force pump during its systole, but during its diastole actively expands and thus gives rise to a negative pressure, which causes blood to move from the systemic veins to the right auricle, has long been maintained. Indeed, while the thorax and lungs are intact there must undoubtedly be some such "suction" action; the elastic reaction of the lungs pulling on the heart must expand it when its walls are relaxed and flabby in diastole. The heart during its systole does extra work in overcoming pulmonary elasticity (as evidenced by the negative pressure then observable in the lungs[1]), and during diastole gets this work returned to it as a distending force.

But the question still remains whether, after the thoracic cavity has been opened, the heart expands in diastole passively in consequence of the positive pressure exerted by blood driven into it from the veins, or actively, and in the latter case, by causing a negative pressure, causes blood to flow towards itself, even when there is no positive pressure in the venæ cavæ? Fick,[2] nearly forty years ago, showed that the hearts of oxen, sheep and men, when in *rigor mortis*, actively expanded after compression; but he also demonstrated that perfectly fresh excised hearts had no such tendency: they only expanded and received liquid from outside when it was sent into them under positive pressure.

It was, however, conceivable that the heart in the living body, with blood flowing through the coronary arteries and capillaries and veins, might behave differently. If we imagine the relaxed

[1] Voit, Zeitsch. f. Biol. I, p. 390; Klemensiewicz, Mitt. d. Ver. d. Aerzte in Steiermark, 1875–76, p. 41: and others.

[2] Müller's Archiv, 1849, p. 283.

heart as a bag with very soft and distensible walls, it is easy to see that a network of distended elastic tubes ramifying in its substance might cause active expansion of its walls and dilatation of its cavities. Starting from this theory, Thebesius and, independently, many years afterwards Brücke, suggested the doctrine of the "*selbst-steuerung*" of the heart. According to this doctrine, the aortic semilunar valves press close against the walls of the vessel during ventricular systole, and cut off the blood-flow to the coronary arteries; these arteries therefore become comparatively flaccid; but during diastole the valves flap back, and blood rushing into the coronaries distends them, and through them the walls of the heart, in which they ramify.

The "*selbst-steuerung*" doctrine in its fullest sense may now be considered as disproved, many facts quite inconsistent with its truth having been demonstrated.

But, although the belief that the mouths of the coronaries are closed during ventricular systole was no longer tenable, it was still possible that the distended elastic arterial branches ramifying in the myocardium should mechanically tend to stretch the walls and dilate the cavities of the heart. During systole the muscular force would easily overcome this stretching tendency of the tense vascular network; but during diastole it is easily conceivable that the muscle might yield in turn and the heart cavities be actively distended. It was to put this question to the test of experiment that the research described in this paper was undertaken. We wished to ascertain whether, at any period of the heart's beat after the thorax had been opened, a negative pressure existed in the right auricle.

The negative pressure proved by Goltz and Gaule to occur in the ventricles for a brief period at the end of the systole, had already been shown by Moens[1] not to affect the auricles, and therefore to be without effect in making the heart a suction pump so far as the venous system was concerned.

The general plan on which we worked was to open the thorax, maintaining artificial respiration and leaving the lungs and the pulmonary blood-flow intact. Then, to place a long tube in the aorta just beyond its arch, and occlude all the branches leading from the aorta except the coronaries. Also, to close the great

[1] Pflüger's Archiv, XX, p. 517.

systemic veins near the heart, except one, which was in connection with a reservoir containing defibrinated blood. This reservoir was connected with the outflow tube tied into the aorta. Thus the whole systemic circulation was represented by the coronary system and a set of rubber tubes which started from the aorta and returned to the right auricle. The heart and lungs being freely supplied with blood, long retained their vitality, and the heart, as we knew by previous work, could in this manner be kept beating normally and vigorously for hours. Then, by connecting a manometer tube, filled with blood, to the side of the cannula leading to the right auricle, and cutting off all blood-supply to the right heart except from this manometer tube, we could easily ascertain whether the right heart exerted a negative pressure, so as to be able, in common phraseology, to "suck" blood out of the manometer after the level of the blood in it was below the level of the right auricle.

The method of experiment was in essential features that described by one of us[1] four years ago. As it has not yet been given in detail in any journal published in the United States, it may be well to here repeat the description, embodying in it such minor changes in the apparatus as have been made since 1883, and a description of the manometer tube and its connections as specially added for the present research.

Small dogs were used; in the present series of experiments they were always deeply narcotized by the subcutaneous administration of sulphate of morphia before the operation was begun. Then tracheotomy was performed, the external jugular vein exposed on one side of the neck, and sufficient curare solution injected into it to prevent reflex muscular contractions. Artificial respiration, maintained uniformly by a small water engine, was started as soon as the curare began to influence the movements of the respiratory muscles.

The further course of the operation was as follows: The pneumogastro-sympathetic trunks were divided on each side of the neck, a cannula put in the right common carotid, and the left ligated. Next, the first pair of costal cartilages and the bit of sternum connected with them were removed, along with the

[1] H. Newell Martin: Direct influence of gradual variations of temperature upon the rate of beat of the dog's heart. Phil. Trans. Roy. Soc. Pt. II, 1883.

episternum; then the internal mammary arteries were tied on their course from the subclavians to the breast-bone. The skin and other tissues covering sternum and costal cartilages were next removed, and the breast-bone and rib cartilages cut away, back to the diaphragm. Then most of the right side of the thorax was removed, any intercostal arteries which spirted being twisted or pinched. The right subclavian artery was prepared, and ligated where it separated from the carotid. The superior vena cava was cleaned, and two ligatures placed loosely around it, to be used subsequently. The right azygos vein was ligated close to its entry into the superior cava, and a ligature was placed loosely around the inferior cava just above the diaphragm.

Proceeding now to the left side of the chest, the subclavian artery was ligated, and, the left lung being gently held aside, the aorta isolated and cleared near the diaphragm. A ligature was placed loosely around the vessel just beyond its arch, and a strong clamp tightened on it to the distal side of this ligature. An aperture having been made in the thoracic aorta near its posterior end, a cannula, filled with defibrinated blood, was inserted into the vessel, and the aortic clamp being removed, was pushed up to the left end of the aortic arch, where the ligature above-mentioned was tied tightly around it. [These aortic cannulas are made of thin brass tubing, and are kept at hand of several sizes, so that one can always be found which fits tightly into the aorta of the animal, and is closely clasped by the elastic walls of that vessel. The cannula has on its distal end a piece of rubber tubing on which is a clamp, which is screwed tight when the tube is filled with defibrinated blood before its insertion into the artery.] The ligature around the inferior vena cava was next tightened, and a cannula filled with defibrinated blood inserted as quickly as possible into the superior cava and tied in place. This cannula was at once connected with *y*, Pl. V, Fig. 1.

So far all the systemic arteries but the coronaries of the heart had been occluded. One common carotid had a cannula in it, and the other was ligatured; both subclavians were ligated below the point at which they gave off any branch, and the aortic cannula was tied in at a level of the vessel, just beyond

its arch, at which it had given off no bronchial or intercostal branches.[1]

The animal was now transferred as quickly as possible to the warm moist chamber, which, with its contents and accessory parts, we have now to describe. It is represented, semi-diagrammatically, in Pl. V, and is 125 centim. in length, 65 centim. in width, and for the greater part of its length is 65 centim. in height. At one end, however, *E*, its height is 130 centim. It has no bottom, but when in use sits in a shallow iron trough (not represented in the figure) filled with water, and raised on supports which admit of Bunsen burners being placed under it; by their means the air in the chest is kept moist and warm. The roof, sides, and one end are glazed; the end, *B*, *E*, is of wood, and perforated by apertures through which several tubes pass. The object of glazing most of the walls of the chamber is to enable a ready view to be had of what is going on inside it; this is apt to be interfered with by condensation of water on the glass during the course of experiment; this drawback may, however, be nearly entirely obviated by smearing the inside of the glass with glycerine. One side of the warm chamber, that turned towards the observer in Pl. V, Fig. 1, is so arranged as to be readily removed and replaced. In it are also several doors which can be opened or closed without removing the whole side of the chamber. These are not represented in the plate. In the chamber are two Mariotte's flasks, *C* and *D*, each of the capacity of two litres. The flasks are entirely similar in all respects, but are so arranged and connected that, at will, either one can in a moment be made to supply blood to the heart or receive blood from it, and always under a constant or any selected pressure, and without opening the warm chamber.

Let us take the flask *C* for more detailed description. Its neck is closed airtight by a rubber stopper through which four glass tubes pass. Two of these tubes, *c* and *d*, end a short way

[1] Sometimes in young dogs a minute branch is given off from the innominate artery to the thymus. This was sometimes tied, but usually neglected, as it is difficult to get at, the amount of blood drained off by it is trivial, and when both venæ cavæ are tied, cannot get back to the heart. The large thymus in puppies makes the operative part of the experiment more difficult in them, but not to any important degree.

below the stopper, and are open to the exterior when the flask is receiving blood. By means of the rubber tubing *l′*, Fig. 1, *c* is connected with the three-way stopcock *X*, Fig. 2, and beyond it, by *l* with the funnels *r* and *x*. From these funnels the flask is supplied with blood. The tube *d*, with its rubber extension, leads to the stopcock *g*, Fig. 2; it, when open, permits the escape of air when blood enters *C* from either of the funnels.

The two remaining glass tubes, *e* and *f*, reach nearly to the bottom of the flask; they are kept closed when *C* is receiving blood, but are opened when it is supplying blood to the heart. Of the two, *f* reaches about half an inch lower than *e*; it is connected by *k* (Figs. 1 and 2) with the three-way cock *W*. From the cock leads the tube *n*, which re-enters the warm chamber, and is connected, during an experiment, with the superior vena cava by the intervention of *o*, *q* and *y*. It serves to supply the heart with blood.

The tube *e* is connected with the stopcock *u*. Through it air enters the flask *C* when it is sending blood to the heart.

The tubes connected with the flask *D* are in all respects similar to those opening into *C*, *c′* answering to *c*, *d′* to *d*, *e′* to *e* and *f′* to *f*, and so forth. The stopcock *X* is so arranged that when the passage from *c* is open that to *c′* is closed, and *W* so that when the passage from *f′* is open that from *f* is shut.

The flasks are represented as resting on the block *S*, in order to avoid more complication in the figure. In reality they stand on a movable platform which can be raised or lowered; and before using they are raised until the bottom of each is about twelve centimeters above the level of *y*, which itself is about 40 centimeters above the bottom of the water trough on which the warm chamber rests.

Before an experiment the flask *C* is nearly filled with defibrinated blood, and *D* about one-fourth filled. This is done from the funnel *r* by opening and closing the proper passages or stopcocks.

The next step is to fill the tube *f* and its fellow, and all the passages connecting them to *y*, with blood from the flasks. These tubes have alternately, during the experiment, to act as syphons, supplying the heart. To fill them, *X*, Fig. 2, is so turned as to close *l′*, and of course *c*, to which it leads; *g* is

turned so as to cut off *d* from communication with the air; *W* is turned so as to open a free passage from *f* through *k* to *n* and thence through *o* and *q* to *y*. Also, *u* is opened so as to place *e* in free communication with the atmosphere. Suction is then applied to *y*, the stopcock *q* being open. Air then enters *C* through *e*, and blood passes out to *y* through *f*, expelling the air previously in the connecting tubes between *f* and *y*. As soon as all the air is expelled the stopcock *q* is shut. *C* is now a Mariotte's flask; on opening *q* it will deliver blood in an even flow and under uniform pressure at *y*, the flask having of course been previously raised so that the lower end of *f* is higher than *y*.

When the tubes connecting *C* with *y* are full, the stopcocks *X* and *W* are reversed; *g* is opened, *u* closed; and *g'* closed and *u'* opened. Then, on *q* being opened and suction again applied at *y*, the tubes leading from *D* to *y* are filled with blood, so that *D* shall act as a Mariotte's flask. Then *q* is closed, *g'* opened and *u'* shut.

The warm chamber is now closed; the stopcocks *X* and *W* again reversed, so that the fuller flask *C* shall be in connection with *y*. But *g* is left open, so that as the blood and air in the flask expand while they heat, air may escape. From time to time *g* is closed and *q* opened; a few centimeters of blood are collected in a beaker and the temperature of the blood noted. This temperature is indicated by the thermometer *p*, the bulb of which reaches into the enlargement *o*. The blood collected is returned to *D* by pouring it into the funnel *r*.

Meanwhile, the preliminary operation on the dog was carried on up to the point of opening the thorax. As soon as the temperature of the blood reached about 38° C., the gas flame under the warm chamber was turned low and the operation on the animal completed, as already described. Then the dog was immediately transferred to the warm chamber, and the cannula in its superior cava connected with *y*. At the same moment *g* was closed so that *C* should act as a Mariotte's flask; then *q* was opened and blood allowed to flow into the right auricle of the heart, under a constant pressure equal to about that of a column of blood ten centimeters in height. The clamp on the rubber tube of the aortic cannula was loosened and the heart allowed to pump out blood in a free stream, but still not so free

but that considerable arterial pressure was maintained in the aortic stump and, from it, in the coronary arteries of the heart. After a minute or so, when it was judged that all the blood previously contained in the isolated heart and lungs had been washed out and replaced by defibrinated blood, the rubber tubing on the end of the aortic cannula was quickly slipped over *h* and the clamp on this tubing removed. The heart then pumped blood up through the tube *t* to the funnel *x*, and from the funnel the blood returned by *l* and its side branch *l''* to *D*. Thus as *C* emptied, *D* filled. When *C* was nearly empty and *D* nearly full, it was easy, by reversing the stopcocks *X* and *W* and opening or closing *g* or *g'* and *u* or *u'*, as the case might be, to make *D* the supplying flask and *C* the recipient. Thus the same blood could be circulated again and again through the heart and lungs, and always be supplied from the superior cava uniformly to the right auricle, while aortic pressure could be kept constant; or, if desired, varied within wide limits by raising or lowering the level of the funnel *x*.

Finally, the cannula in the right carotid having been connected with a mercury manometer, which recorded arterial pressure and the pulse rate on the paper of the kymographion, the front of the warm chamber was replaced.

Of course, artificial respiration was maintained throughout the experiment. The air-supply tube from the respiration pump leads to a three-way stopcock; one branch of the stopcock opens into a tube which leads to the operating table; the other branch into a tube which leads into the warm chamber. As soon as the animal is removed from the table to the chamber, the stopcock is turned so that the air blast enters the tube leading to the warm chamber, and this is immediately connected with the cannula in the trachea.

By means of the thermometer *p* the temperature of the blood supplied to the heart can be ascertained; this can be kept fairly uniform by raising or lowering the flames of the Bunsen burners beneath the warm chamber, as desirable. We also found it useful to surround with raw cotton the parts of the tubes *t* and *l* which lie outside of the chamber. By surrounding *C* and *D* with water jackets[1] the blood supplied to the heart

[1] Phil. Trans. Roy. Soc. Lond., Pt. II, 1883.

can be kept at an almost uniform temperature. But as such uniformity was not necessary in regard to the experiments to be described in the present paper, the water jackets were not used. The blood was in every instance kept near 38° C., and never varied more than 2° C. from that temperature during the time in which our observations were made.

It still remains to describe that part of the apparatus, viz. *abm*, which was specially devised for the series of experiments to be described in this paper. Between *q* and *y* is intercalated the top of a T-piece; on the leg of this T-piece is the stopcock *a*. When this is closed, all blood passing *q* must take its course to the heart through *y*; but if *a* be opened, some of the blood will flow into the U-tube *bm*, which is fixed at such a level, after the animal has been put in the warm chamber, that the upper end of the open limb *m* is above the level of the right auricle of the heart. The limb *b* can be opened or closed at will by the stopcock *s*.

So soon as the heart was ascertained to be pumping blood round well and uniformly, *a* and *s* were partly opened and a portion of the blood-supply diverted until the U-tube was filled to near the top of *m*. Then the stopcocks were closed, and all the blood again flowed through the heart. Next, the height of the point of entry of the superior cava into the right auricle was carefully measured from the bottom of the warm chamber. This was done by placing the lower edge of one end of a spirit-level on the cannula connected with *y*, and close to the heart. After getting the level perfectly horizontal, the distance of its lower edge from the bottom of the trough was measured. This gave the height above the bottom of the trough of the upper side of superior cava where it joined the auricle.

If now *q* be closed and *a* opened, the right heart no longer can get blood from the Mariotte's flask. Its only source of supply is from the previously filled U-piece. If it takes blood from this until the level of the liquid in *m* falls below the level at which the vena cava enters the auricle, then the right heart has exerted some suction, it has actively expanded; while if it only continues to supply itself so long as the level of the blood in *m* is higher than the level of the entrance to the auricle, it is clear that the heart only takes blood when supplied to it under some

positive pressure, and that it is not a suction pump. So soon as the level of the blood in *m* ceased to fall, its height from the floor of the trough was measured and noted. Then *q* was opened, and the heart thus again is supplied with blood from one of the Mariotte's flasks, while the U-tube *bm* was also refilled. Then *a* was closed. After waiting a minute or two, *q* was once more closed and *a* opened, and the observation repeated; and so on as often as might be desired, or until the heart began to show symptoms of weakening.

We made in all nine experiments as to the capacity of the right heart to actively take blood from the superior cava after the thorax had been opened; and in the course of each experiment the conditions were varied. At the commencement arterial pressure was medium (about 95 mm. Hg), and the pericardium was intact. Then arterial pressure was varied within wide limits, by raising or lowering the level at which *t* emptied into *x*. Moderate and violent artificial inflation of the lungs were employed, and also the entire cessation of the artificial respiration. Finally, in order to give the heart the greatest possible freedom, the pericardium was cut away, and the observations repeated. But in no single case did we find that the right auricle would receive blood unless that blood were supplied to it under positive pressure, the minimum pressure required varying little from that exerted by a column of blood about 12 mm. in height. It might fall to 8 mm. or rise to 18 mm., but those were the limits.

The earlier experiments were made with the defibrinated blood of young sucking calves. Though the isolated heart of the dog will work well for hours when supplied with this blood, it was possible that it might injuriously affect the elasticity of the heart muscle, so our final experiments were made with the hearts of dogs supplied with defibrinated dog's blood, obtained by bleeding several large animals immediately before the experiment. We append the protocols of two such experiments; as all the others agreed with them in every essential, it is not worth while to print them in detail.

The outcome of our work is this: that once the "aspiration of the thorax" has been eliminated, the right auricle of the mammalian heart will not receive blood unless supplied to it under a decided, if small, positive pressure. While the heart in the

closed thoracic cavity may, and probably does, act as a suction pump, this is not due directly to an active expanding force of the heart, but is the secondary result of the pneumatic conditions prevailing within the normal closed chest cavity. Any cause diminishing thoracic aspiration must therefore greatly hinder the work of the heart; and it is probably more in this manner that the circulation is impeded in certain cases of hydro- or pneumothorax than by direct pressure exerted on the heart itself.

In the experiment protocols appended there are six columns. Column I gives the time; column II, the height of the upper side of the vena cava superior from the floor on which the warm chamber rested; column III, the lowest height of the blood in the manometer tube *abm*, Plate V, Fig. 1, at which the right auricle would receive blood, this height being measured from the floor of the warm chamber; column IV, the differences between the heights recorded in columns II and III, that is, the lowest pressure under which the heart would receive blood from the systemic veins; column V gives arterial pressure as measured by the manometer connected with the right common carotid; in column VI are given notes when necessary.

Experiment of December 2, 1886.

Dog under morphia and then curare.—Defibrinated dog's blood used.

I.	II.	III.	IV.	V.	VI.
Time. P. M.	Height of upper side of vena cava superior from floor of warm chamber, in millimeters.	Lowest height at which right auricle would take blood, in millimeters.	Minimum positive pressure necessary in order to make right auricle take blood, in millimeters of positive blood pressure in the vein.	Arterial pressure in right carotid, in mm. of mercury.	Notes.
h. m. 3.35	412	435	23	130	
3.38	"	447	35	164	Respiration moderate and uniform.
3.42	"	430	18	103	
3.44	"	427	15	80	
3.45	"	432	20	105	
3.46	"	435	23	142	
3.48	"	450	38	183	
3.53	"	432	20	130	The apparatus for artificial respiration was readjusted at 3.54 so as to make the respiratory movements of the lungs violent, both in expiration and inspiration.
3.55	"	462	50	130	
3.56	"	432	20	130	Artificial respiration stopped at 3h. 55′ 50″
3.59	"	432	20	130	Arterial pressure again was varied, while respiration was kept constant and uniform.
4.01	"	445	33	172	
4.03	"	455	43	200	
4.05	"	442	30	135	
4.06	"	440	28	118	
4.07	"	430	18	75	
4.08	"	442	30	125	
4.11	"	452	40	183	
4.13	"	512	100	205	This arterial pressure was too much for the heart to overcome. It began to dilate, and the experiment was ended.

Experiment of December 3, 1886.

Dog under morphia and then curare.—Defibrinated dog's blood used.—Respiration varied both in force and frequency during the experiment, and at other times kept constant while arterial pressure was varied.

I.	II.	III.	IV.	V.	VI.
Time. P. M.	Height above floor of warm chamber of upper side of vena cava superior, in millimeters.	Lowest height at which right auricle would take blood, in millimeters.	Minimum positive pressure necessary in order to make right heart take blood, in millimeters of positive blood pressure in the vein.	Arterial pressure in right carotid, in millimeters of mercury.	Notes.
h. m. 3.44	410	437	27	125	Artificial respiration 24 per minute and moderate.
3.46	"	437	27	125	Respiration stopped.
3.48	"	430	20	125	Respiration violent.
3.50	"	435	25	115	Respiration moderate, and 24 per minute from this time on.
3.52	"	435	25	85	
3.54	"	432	22	110	
3.56	"	440	30	130	
3.58	"	455	45	150	
4.02	"	480	70	170	Heart begins to dilate.
4.05	"	507	97	182	
4.08	"	455	45	125	
4.10	"	440	30	97	
4.12	"	440	30	75	
4.14	"	442	32	130	
4.15					Pericardium cut away.
4.16	"	432	22	130	
4.18	"	435	25	145	
4.20	"	437	27	165	
4.22	"	445	35	200	
4.24	"	440	30	160	
4.26	"	435	25	135	
4.28	"	432	22	100	
4.30	"	432	22	90	
4.32	"	438	28	135	
4.34	"	445	35	175	Experiment ended; heart and lungs being still in very good working condition.

Fig. 1. Fig. 2.